# TROPICAL CYCLONE PROPAGATION

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## 1. INTRODUCTION

This paper discusses tropical cyclone (TC) propagation which is defined as the difference in TC motion from outer radius deep layer steering flow movement. Previous analyses have shown that the 5-7° radius 850-300 mb layer mean flow give a reasonably good representation of the tropical cyclone's steering environment (Chan and Gray, 1982; Gray *et al.*, 1988).

The author has made many new TC motion related rawinsonde composite analyses for northwest Pacific, Atlantic, and the Australia-South Pacific tropical cyclones. Composite data have been stratified by three motion direction categories (west, north, and northeast) and three speed (slow, average, and fast) categories. Stratification has also been made for stationary or nearly stationary cyclones in each basin. Special software programs have been developed to calculate the surrounding cyclone deep layer wind components parallel and perpendicular to the fixed and moving cyclone center. A primary purpose of these analyses has been to quantitatively document the relationship between the tropical cyclone's center motion and its surrounding deep layer (850-300 mb) winds at various radii. These composited data sets show that:

1. Tropical cyclones move with a speed and direction very close to their interior, 1-3° radius tropospheric mean wind currents. There is little propagation component of the cyclone center motion relative to its deep layer interior translation or steering flow.
2. There are systematic and progressive differences between TC motion and the average 850-300 mb outer radius winds at 3-5°, 5-7°, 7-9° and 9-11° radius. Tropical cyclones move systematically and progressively with radius faster and to the left (for N. Hemisphere orientation) of their outer radius deep layer mean flow (except for westward moving Atlantic cyclones which move faster but slightly to the right of their deep layer steering current because of special Atlantic environmental conditions).

Figure 1 illustrates how the tropical cyclone center and the mean winds at 2° and 4° radius move systematically faster and to the left of the outer 6° and 8° radii winds. This is true for nearly all of our speed and direction rawinsonde motion stratifications. Westerly, northerly and northeasterly moving tropical cyclones are all observed to have roughly the same 6° and 8° speed and direction orientations in relation to their interior 2° and 4° wind vectors. (See Appendix Fig. A1).

A primary theme of recent theoretical TC motion research has been to explain the physical processes responsible for tropical cyclones having a propagation component relative to their surrounding deep layer environmental steering currents. Why do tropical cyclones always move faster than their surrounding steering flow and almost always to the left of this flow? A major methodological approach to an attempted better understanding of TC propagation has been involved with barotropic modeling on a Beta plane. Barotropic numerical modeling efforts of the last few years have been carried on by a number of researchers [Holland (1983); DeMaria (1985, 1987); Chan and Williams (1987); Willoughby (1988); Smith (1989); Fiorino and Elsberry (1989); Evans *et. al.* (1990); Carr (1989); Carr and Elsberry (1989); and others].

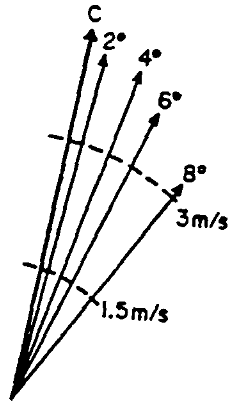


Figure 1: *Synthesis of the TC motion vector (C) relative to the 850-300 mb mean wind in the 2° (1-3°), 4° (3-5°), 6° (5-7°) and 8° radial belts.*

Although there are some differences between the various barotropic simulations and their interpretations, there has been a general unity of view that Beta drift is a dominant influence on cyclone propagation. This may be a correct interpretation as regards one-level model simulation but may not be very representative of the real world propagation for tropical cyclones which exist within a baroclinic atmosphere where Beta-induced propagation influences can act in different directions and with different magnitudes in the vertical. Such potential vertical varying influences likely introduces complex and partially cancelling propagation responses in comparison with single level flows.

Other one-level numerical model runs have been run with the added influence of horizontal gradients of relative vorticity (De Maria, 1985, 1987). It has been found that one layer vortex propagation can also be significantly influenced by the varying horizontal gradients of relative vorticity in which the cyclone might exist.

It is likely that these many barotropic propagation simulations have neglected certain essential processes that may play a primary role in real world tropical cyclone propagation. This supposition should likely be given consideration, particularly if the results of such barotropic simulations are not well substantiated in the observations. For example, our rawinsonde compositing studies of stalled and slowly moving

($< 3ms^{-1}$) tropical cyclones in the NW Pacific and Atlantic basins show no obvious northwest propagation of the tropical cyclone center relative to the ambient surrounding 850-300 mb mean wind flow. (See Appendix Fig. A2). We also do not find that the inner-radii winds of eastward moving tropical cyclones move slower than outer radii winds as Beta-drift theory would imply. Eastward moving cyclones and inner radius deep layer flows are observed to track as fast or faster than their surrounding outer radius flows. (See Appendix Fig. A1). Such inconsistency with Beta-drift theory for eastward moving cyclones cannot be explained by differences in the gradients of relative vorticity between east versus west tracking cyclones as some researchers have suggested. Observations do not support large differences in the relative orientations of the gradients of relative vorticity for eastward versus westward moving cyclones. We also do not observe that typhoons and hurricanes with very strong outer radii tangential circulations possess larger forward and leftward propagation components than cyclones with substantially weaker outer circulations as implied by the barotropic simulations of Chan and Williams, 1987. We observe that propagation is very similar for cyclones with different strength outer circulations as it is for cyclones moving in different directions. Propagation appears to be largely independent of cyclone structure and of Beta orientation.

The author does not question the validity of any of the barotropic propagation simulations but only their applicability to real world TC propagation. It is likely that because of the special baroclinic environment in which the TC exists that significantly different cyclone propagation related factors are in operation than those specified by one-level dynamics. Such vertical varying factors may cause real world TCs to propagate differently from those processes specified by one level model simulations.

The added complexity of environmental baroclinicity influences on cyclone propagation have yet to be well sorted out in either an observational, theoretical, or numerical modeling context. This paper proposes a new approach to the interpretation of TC propagation. I will attempt to explain real world tropical cyclone propagation as primarily a consequence of processes associated with the existence of the TC vortex within its special baroclinic environment.

## 2. HYPOTHESIS

The author hypothesizes that TCs move faster than their outer radii deep layer flow because of the baroclinic character of the environmental current in which the moving tropical cyclones exist. By orienting ones self in the direction of cyclone movement, it is observed that the cyclone's tropospheric environment has warm air on its right side and cold air on its left side throughout its deep layer flow. This baroclinic steering environment causes upward and leftward slope of the cyclone's surrounding environmental flow features. All moving tropical cyclones irrespective of direction exist in a tropospheric environment having right side (warm) to left side (cool) baroclinic environments. These environmental baroclinic influences lead to a leftward vertical slope of the monsoon trough or the frontal system near which the tropical cyclone forms or exists. It also causes a similar leftward upper slope of the subtropical ridge on the tropical cyclone's right side. It is well known that tropospheric troughs and ridges slope with height to their cold air sides. This typical leftward upward slope of the cyclone's environmental flow features for westward and northward moving cyclones is shown in Fig. 2. The cyclone center is located at the warmest location and has no vertical shear of environmental wind around its center. To the north or the right side of the top diagram, the environmental trade winds weaken with height and westerlies are present in the upper troposphere. To the left or south side, environmental wind shears are opposite to those on the right side. Low level winds are weak but increase with height to become strongly easterly in the upper troposphere. Note the north to south upward vertical slope of the subtropical ridge. Note also a similar north to south or right to left upward slope of the monsoon trough.

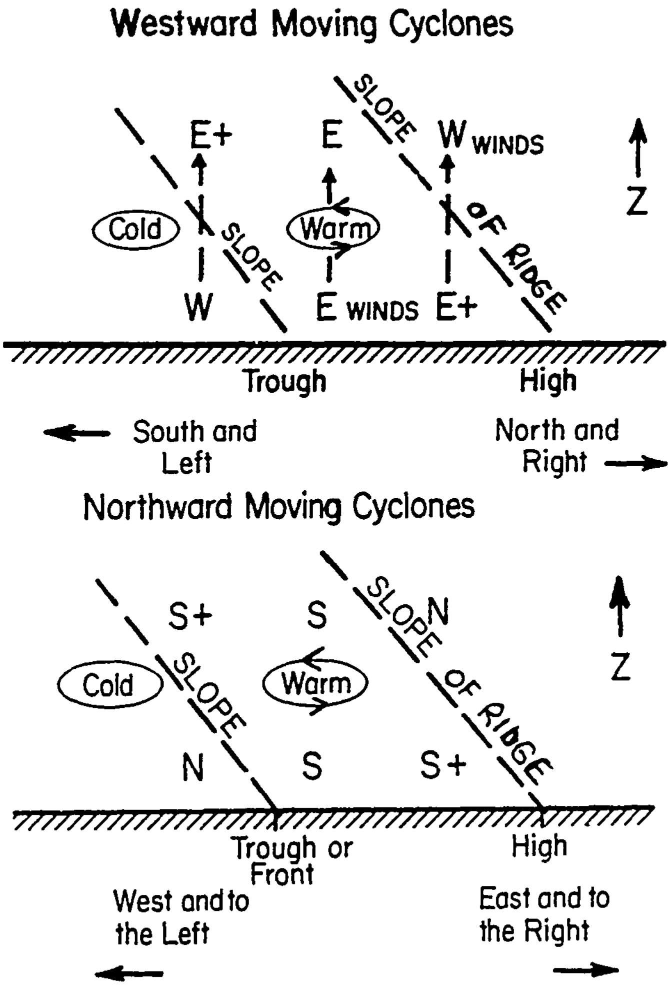


Figure 2: *Vertical cross section of the tropical cyclone's typical environmental wind components parallel to its motion for westward moving cyclones (top diagram) and northward moving cyclones (at bottom). E, W, N, S stand for the direction from which the environmental wind is blowing. The cyclone is located at the warm designation.*

The bottom diagram of Fig. 2 is an analogous figure but for northward moving cyclones. It shows a similar leftward or to the west upward vertical slope of the cyclone's surrounding environmental wind patterns. The subtropical ridge to the right side slopes with height toward the cyclone, the trough or frontal system to the left side slopes with height to the cold air on its left. A very similar type of environmental slope occurs (not shown) for those tropical cyclones moving northeastward

There is thus a general similarity of the vertical variations in the moving cyclone's right to left environmental wind fields regardless of the cyclone's direction of motion. These typical vertical slopes of surrounding wind fields can be idealized as in Fig. 3. Typical vortex subtracted and rotated environmental wind velocities parallel to the cyclone's motion are shown. In this case the cyclone is moving at 3 units of environmental velocity. Note that at the location of the cyclone center there can be no vertical wind shear. Environmental 850 mb and 200 mb pressure-height lines show the characteristic leftward upper slope of the environmental flow conditions. These typical pressure-height slopes cause the vertical variations of the parallel environmental winds which are shown. The parallel component of the environmental wind on the right side decreases with height from 4 to 1 units. The environmental parallel wind component on the left side increases from 1 unit at the lower level to 4 units at upper levels. Note that such environmental flow conditions would exist irrespective of whether a tropical cyclone were present or not.

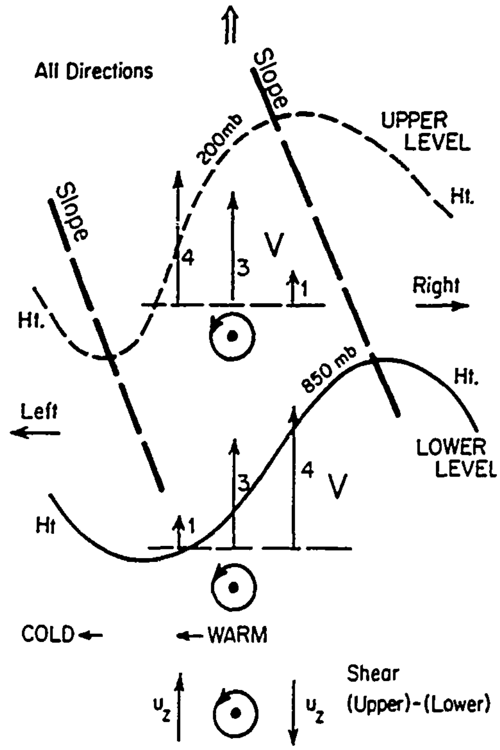


Figure 3: *Idealized vertical cross section of the typical slope of the tropical cyclone's left to right environmental 850 mb and 200 mb height fields with associated idealized environmental wind components parallel to the cyclone motion. Cyclone winds are not included. The cyclone and the winds are directed into the paper. This typical picture is valid for all cyclone direction orientations.*

It is these vertical changes in the cyclone's surrounding environmental parallel wind components which are responsible for the cyclone's characteristic faster than environmental motion and its general propagation component. Cyclones move faster than their environmental flow because the deep layer mean environmental winds on their right and left sides are slower than the deep layer environmental winds which blow across the cyclone center. Figure 4 is similar to Fig. 3. It shows the corresponding environmental mean tropospheric wind conditions associated with the flow fields of Fig. 3. Note in Fig. 4 that the mean parallel component of the two level winds near the cyclone center is 3 units while the two level or deep layer parallel components to the right and left sides are but 2 1/2 (or one-half of 4 plus 1 units) or 1/2 unit less than at the center. This results in forward propagation.

Tropical cyclones thus move faster than their environmental 4°, 6°, or 8° radial winds because of the character of the baroclinic environment in which the cyclone vortex is embedded. One does not have to resort to Beta–drift arguments to explain such forward propagation.

Note in the top diagram of Fig. 5 that the cyclone's vortex exists on the right side of the maximum low level horizontal shear of the parallel environmental wind, V, defined to be positive in the direction of cyclone motion. If x is taken from left to right across the vortex, then 850 mb $\frac{\partial^2 V}{\partial x^2}$ is negative. At 200 mb the maximum left to right parallel environmental horizontal wind shear is to the right side of the vortex but $\frac{\partial^2 V}{\partial x^2}$ is still negative. The top diagram of Fig. 5 and the conditions shown in Fig. 6 portray these typical horizontal wind shear conditions which are observed and which are largely independent of cyclone direction of motion. Table 1 shows rawinsonde derived measured right minus left quadrant parallel component of the mean environmental winds in the direction of cyclone

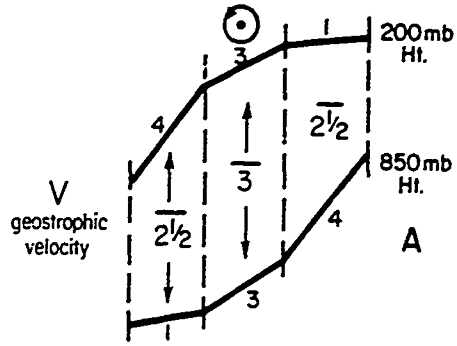


Figure 4: *Idealized cross section of the typical slope of the 200 and 850 mb environmental height field to the right and left of a moving cyclone with the resulting deep layer mean parallel component of the gradient winds. 850 and 200 mb level averages 3 units around the cyclone center but only 2 1/2 units (half of 4 + 1) to the right and left of the cyclone.*

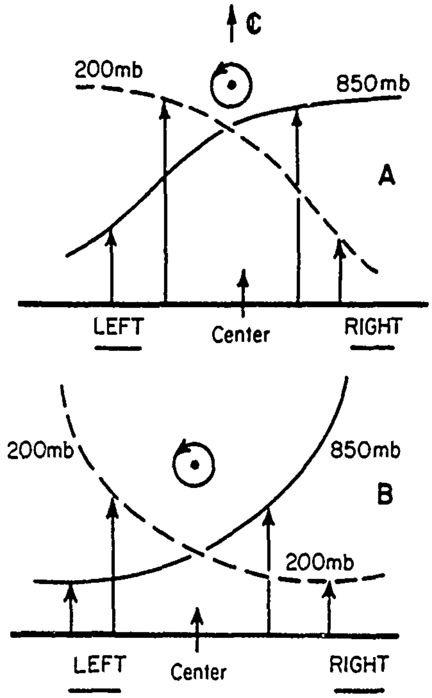


Figure 5: *Contrast of opposite types of left to right environmental wind parallel to the direction of cyclone motion at 850 and 200 mb. Diagram A is for conditions as they are observed and for which forward cyclone propagation results. Diagram B shows opposite horizontal shear patterns which would, if such shearing conditions existed lead to negative or backward propagation. Diagram B conditions are not observed, however.*

motion where the mean cyclone vortex winds have been subtracted out of each wind. This table shows the mean values of all west, north, and northeast moving cyclones in the NW Pacific and the Atlantic. Individual composites differing in cyclone direction, speed and ocean basin values give similar values. Inspection of Fig. 6 shows that $\frac{\partial^2 V}{\partial x^2}$ at 200 mb and $\frac{\partial^2 V}{\partial x^2}$ at 850 mb are always observed to be negative for all moving cyclone directions. The speed of forward propagation ($P_F$) of the cyclone vortex relative to its mean tropospheric 5-7° radius 850-300 mb average wind can be approximated as:

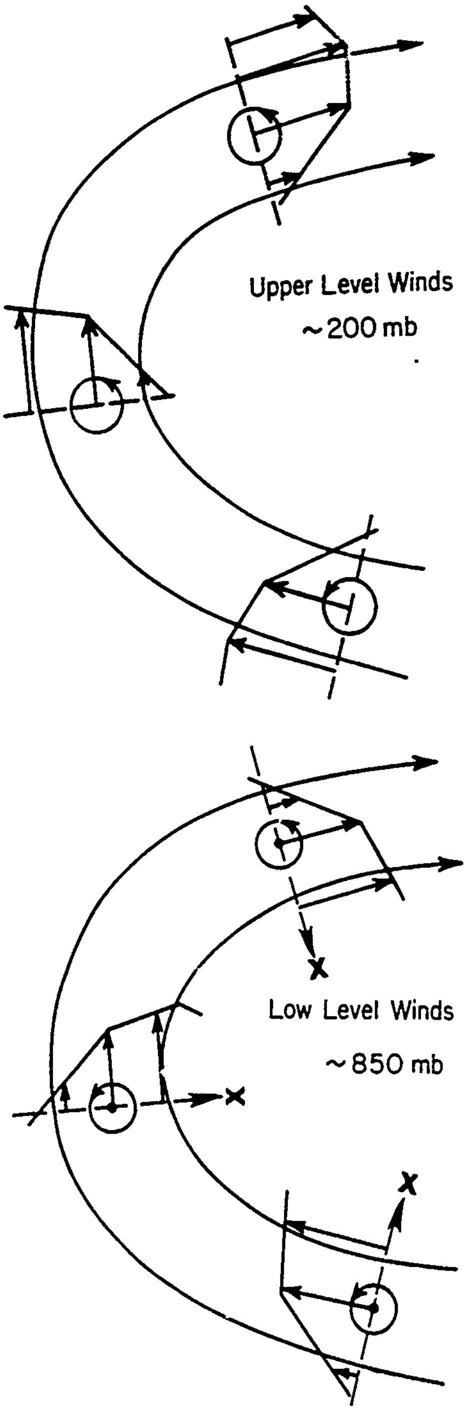


Figure 6: *Idealized plan view representation of typical horizontal (or $x$ direction) shear of the environmental parallel wind ($V$) across moving cyclones at upper and lower tropospheric levels. Note that $\frac{\partial^2 V}{\partial x^2}$ is negative at both levels for all direction categories.*

$$P_F = -K\left[\frac{\partial^2 V}{\partial x^2})_{200mb} + \frac{\partial^2 V}{\partial x^2})_{850mb}\right] \qquad (1)$$

where

K is an empirically determined constant equal to about 3 X $10^5$ m for deep layer horizontal shear determination between 6° radius to the right and left.

Substitution of observational values into Eq. 1 gives forward propagation values of about 1-3 m/s relative to the 5-7° mean tropospheric wind which matches observations.

Table 1: *Rawinsonde measured average right minus left quadrant (MOTROT–VORT.) wind or the wind of the environmental parallel to the direction of the moving cyclone center (m/s).*

| | Radius | | | |
|---|---|---|---|---|
| | 3-5° | 5-7° | 7-9° | 9-11° |
| 200 mb | −3.0 | −7.3 | −10.4 | −11.9 |
| 850 mb | 2.0 | 1.5 | 1.5 | 1.7 |
| $-[(\frac{\partial^2 V}{\partial x^2})_{200} + (\frac{\partial^2 V}{\partial x^2})_{850}]$ | 5.0 | 8.8 | 11.9 | 13.6 |

MOTROT is the coordinate system where the vector of cyclone motion has been subtracted from all the wind and all the wind reports have been oriented with respect to the direction in which the cyclone moves. VORT refers to the mean vortex tangential winds. MOTROT–VORT means that mean vortex winds have been subtracted from all MOTROT winds. This representation gives the resultant environmental wind parallel and relative to the cyclone center.

If, by contrast, the right to left side environmental shear patterns were to be arranged oppositely as indicated on the bottom diagram of Fig. 5, then the right hand side of Eq. 1 would be negative and the environmental tropospheric flow near the cyclone center would be slower than the surrounding 5-7° mean tropospheric winds. A backward or negative cyclone propagation would then occur. But this is not observed. If the $\frac{\partial^2 V}{\partial x^2}$ of the horizontal shears at both levels across the cyclone were zero, then so too would be forward propagation.

## 2.1 Cyclone Leftward Propagation

Except for westward moving cyclones in the Atlantic, which have special environmental conditions (discussed in other papers) all of our rawinsonde composite stratifications show a consistent movement of the tropical cyclone's inner core 1-3° radius deep layer mean wind 10 to 25° to the left of the direction of the 5-7° 850-300 mb deep layer mean wind. This generalized leftward motion of the cyclone's inner core region is hypothesized to be a natural consequence of the TC's faster inner-core forward propagation. This faster inner radius propagation causes a front to rear quadrant tangential wind asymmetry at inner radii relative to the front minus rear outer radius winds. This causes the inner vortex to move to the left of the outer vortex. We find that leftward propagation ($P_L$) is roughly equal to forward propagation ($P_F$). A more complete discussion of leftward propagation will be given in future papers.

It is also possible to interpret the leftward propagation in terms of the horizontal gradient of environmental relative vorticity. Note in Fig. 6 that there is higher environmental relative vorticity to the left than the right side of the cyclone at both lower and upper tropospheric levels. This environmental relative vorticity gradient to the left side might also be used as a complementary argument to explain leftward propagation. But realize that this right to left side gradient in relative vorticity is a result of the inherent deep layer environmental baroclinicity field in which the tropical cyclone is embedded and not a consequence of a horizontal vorticity gradient within a barotropic flow field. In addition to forward propagation, leftward cyclone propagation is also seen to be a consequence of the baroclinic environment in which the cyclone exists.

## 3. SUMMARY

Our special cyclone motion related rawinsonde composite analyses indicate that tropical cyclone propagation is primarily a result of the tropical cyclone's existence within its special baroclinic environment with an upward and leftward sloping subtropical ridge to its right side and an upward and leftward sloping monsoonal trough or front to its left. This baroclinic environmental flow is such as to cause deep layer "baroclinic-gyres" similar to the type of single level gyres developed in the barotropic motion simulations.

Tropical cyclones typically move in a clockwise manner (in the Northern Hemisphere) around a warm subtropical high pressure system on their right sides. A relatively cool monsoon trough or frontal system is almost always present on the tropical cyclone's left side. The resulting deep layer environmental right side (warm) to left side (cold) horizontal temperature gradient across the cyclone introduces a vertical right to left upward slope of the cyclone's surrounding environmental flow features which is the primary cause of TC propagation and not Beta-drift.

The leftward propagation of the tropical cyclone is a consequence of the forward cyclone propagation which causes the establishment of front minus rear tangential wind asymmetries at inner radii which are stronger than at outer radius. These front minus back wind asymmetries induce a leftward motion of the inner-core vortex relative to its outer radius flow. This leftward propagation might also be thought of as a result of the higher environmental vorticity to the leftward side of the cyclone vortex.

As most forward and leftward TC propagation measurements have been made on cyclones moving in a westerly or northerly direction, it has been appealing to interpret such propagation measures as a consequent of the northwesterly Beta-drift inherent in Beta-plain one layer modeling results. But these Beta-drift interpretations appear to be an incorrect and unfortunate analogy for real world tropical cyclones. Another more physically reasonable arguments for TC propagation are available.

## 4. ACKNOWLEDGEMENT

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## 5. APPENDIX

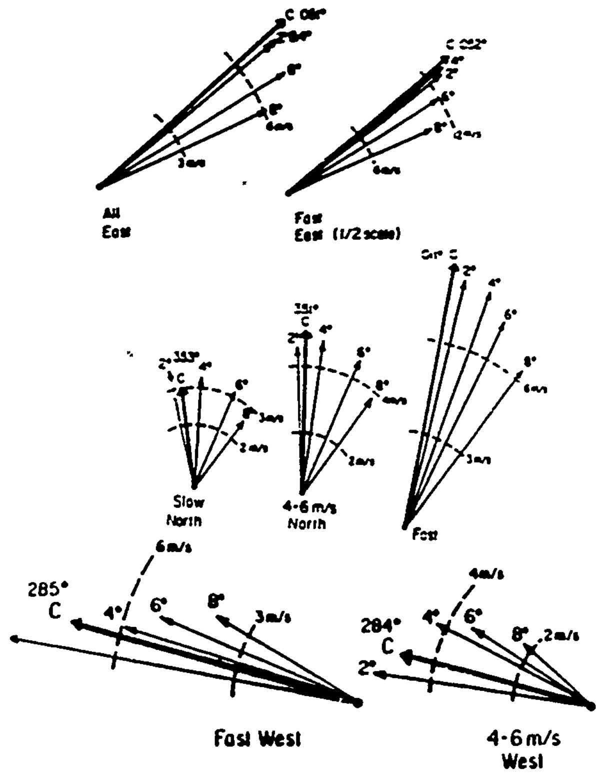


*Figure A1: Layer average (850-300 mb) symmetric wind vectors in various radial bands relative to the mean cyclone motion (C). Stratifications are by cyclone speed for NW Pacific northeasterly (top), northward (middle), and westerly moving cyclones. 2° is 1- 3° mean radial motion, 4° is 3-5° mean motion, etc.*

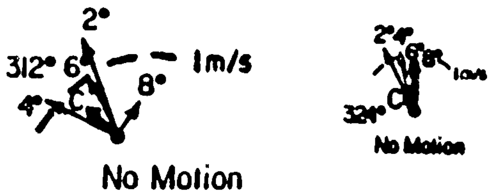


*Figure A2: Stratification of 850-300 mb mean winds for cyclones with speeds of 3 m/s or less (cyclone vector is C) in the NW Pacific (left) and the West Atlantic (right). There is no obvious northwest draft of C relative to the outer radius winds.*

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